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CASE STUDY

Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters

Rosario Vidal · Pilar Martínez · Daniel Garraín

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Abstract

Background, aim, and scope The goal of this study is to analyze the environmental impact of new composite materials obtained from the combination of recycled thermoplastics (polypropylene [PP] and high-density polyethylene [HDPE]) and biodegradable waste of little economic value, namely, rice husks and recycled cotton. The environmental impact of these materials is compared to the impact of virgin PP and HDPE using life cycle assessment.

Materials and methods From-cradle-to-grave life cycle inventory studies were performed for 1 kg of each of the three new composites: PP+cotton linters, PP+rice husks, and HDPE+cotton linters. Inventory data for the recycling of thermoplastics and cotton were obtained from a number of recycling firms in Spain, while environmental data concerning rice husks were obtained mainly from one rice-processing company located in Spain. Life cycle inventory data for virgin thermoplastics were acquired from PlasticsEurope. Two different scenarios—incineration and landfilling—were considered for the assessment of disposal phase. A quantitative impact assessment was performed for four impact categories: global warming over a hundred years, nonrenewable energy depletion, acidification, and eutrophication.

Results The composites subject to analysis exhibited a significantly reduced environmental impact during the materials acquisition and processing phases compared to conventional virgin thermoplastics in all of the impact categories considered. The use of fertilizers for rice cultivation, however, impaired the results of the rice husk composite in the eutrophication category where it nevertheless outperformed its conventional counterparts. The compounding phase fundamentally implies an electric consumption. The disposal phase was analyzed with regard to emissions in the global warming category.

Discussion Composites obtained from renewable sources are still in an incipient state of development in comparison with petroleum-derived plastics. In the future, as mass production of these plastics becomes more widespread, their environmental impact can be expected to reach lower levels than those obtained in our study. The new materials exhibited adequate mechanical performance for the application analyzed (structures used in aquaculture).

Conclusions The composites subject to analysis exhibited a significantly reduced environmental impact compared to conventional virgin thermoplastics using 1 kg of material as a functional unit.

Recommendations and perspectives In accordance with the International Organization for Standardization 14044:2006 standard, it would be advisable to avoid impact allocation. This posed some difficulties, since rice husks are a coproduct of rice. Thus, some impact allocation was done in our study on the basis of economic value. It would also be advisable to take the land use impact category into consideration when performing comparative studies between composites and conventional plastics, albeit the definition of this category is currently the subject of scientific debate.

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R. Vidal (✉) · D. Garraín
GID, Engineering Design Group, Dpt. MEC, Universitat Jaume I,
Av. Sos Baynat, s/n,
E-12071 Castellón, Spain
e-mail: vidal@emc.uji.es

P. Martínez
AIMPLAS, Technological Institute of Plastics,
València Parc Tecnològic,
C/Gustave Eiffel, 4,
E-46980 Paterna, Valencia, Spain

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1 Background, aim, and scope

It is difficult to imagine modern life without plastics. Conventional plastics have earned a dominant position in numerous fields over other materials such as wood, metals, glass, ceramics, etc., thanks to their low manufacturing costs (moderate energy requirements), low density, small weight, and excellent mechanical, thermal, chemical, and optical properties.

The rapid development of polymers over the past decades was mainly due to the ability to engineer modified plastics, combining them with other substances (fillers, reinforcing fibers, stabilizers, plasticizers, etc.) which are incorporated into their structure for improved performance.

From the environmental point of view, however, the picture may not look so bright. Conventional plastics—fossil fuel-derived polymers—not only consume nonrenewable finite resources, but also impact heavily upon waste disposal. The development of alternative biodegradable polymers and composites seeks to overcome the disadvantages found in conventional polymers. On the other hand, some authors have stated that bio-based materials may, in some cases, be less “ecological” than their conventional counterparts. This paradoxical situation could be due—among other reasons—to the high degree of optimization attained by conventional plastic-processing industries. A discussion on this matter can be found in Garraín et al. (2007a, b).

Composite materials can be defined as those materials having two or more constituent phases. Some composites have polymeric matrices, which may either be derived from renewable resources or—more commonly—be composed of synthetic, fossil fuel-derived polymers featuring variable proportions of virgin and recycled thermoplastics. Reinforcements and fillers for these plastics can be selected from a vast array of materials, including plant fibers, recycled wood, paper, nonsynthetic textiles, or even by-products of food crops.

Over the past decade, the use of composites has grown considerably in the field of wood decking and in the automotive industry with countless new applications now being envisioned for the future (Fowler et al. 2006). Yet, in order to confirm such optimistic prospects, we need to properly assess the environmental performance of these new materials throughout their entire life cycle; from raw material acquisition to disposal.

Some life cycle assessment (LCA) studies of composites can be found in the literature. Diener and Siehler (1999) deal with an underfloor panel used to protect the chassis while improving the aerodynamics of the Mercedes-Benz A-class car. In one case study, the panel was made from fiberglass-reinforced polypropylene (PP) and in the other from PP reinforced with flax.

Wötzel et al. (1999) and Gärtner and Reinhardt (2004) performed LCA studies of automotive parts. In both studies, the conventional part was manufactured by injection molding of virgin acrylonitrile–butadiene–styrene, while the bio-based component was made of a composite consisting of hemp fibers and epoxy resin plus hardener.

The LCA made by Corbière-Nicollier et al. (2001) compared a pallet made from fiberglass-reinforced PP to a pallet manufactured from a PP+china reed fiber composite.

This paper presents the results obtained from the LCA of a type of plastic composites reinforced with organic fiber/filler (rice husks and recycled cotton linters). The newly developed composite materials were obtained by incorporating the selected crop waste into a recycled thermoplastic matrix (PP or high-density polyethylene [HDPE]) to improve its environmental performance. The use of a recycled polymeric matrix was a design priority. These composites were specifically developed to build structures used in aquaculture (in permanent contact with water) (Martínez et al. 2007). The composite materials were engineered to have the highest proportion of biodegradable waste while retaining the mechanical properties required by their intended use. The availability of polymer-processing technologies suitable for their manufacturing was also considered.

The environmental impact of these new composites was compared to the impact of virgin PP and HDPE. The environmental impact of plastics is not unrelated to their disposal method. When the product becomes waste, the thermoplastics exhibit different behaviors depending on whether they are incinerated or taken to landfill. These two scenarios were analyzed for both the conventional thermoplastics and the new composite materials.

2 Materials and methods

2.1 Goal, functional unit, scope, and data quality

The goal of this study is to analyze the environmental impact of newly developed composite materials obtained from the combination of recycled thermoplastics (PP and HDPE) with rice husks and recycled cotton, which are biodegradable waste of little economic value. The environmental impact of these materials is compared to the impact of virgin PP and HDPE. Additionally, the impact associated with the disposal of each material is assessed for two different scenarios: landfilling and incineration.

Provided that the new materials exhibited adequate mechanical performance as structures for aquaculture—

somewhat lower but comparable to that of conventional plastics (European project DOLFIN, contract COOP-CT-2003-508682)—1 kg of material was defined as the functional unit used in this study for calculations and comparative purposes. In Section 4, a discussion is offered on the variation of results that could be expected due to an alternative definition of the functional unit in terms of volume.

The impacts associated with the transport of recyclable plastic to the recycling plant, the recycling process of plastic, the transport of recycled plastic to the compounding plant, and the compounding process were considered for the assessment of both types of composites. In the case of composites containing cotton linters, the impacts associated with the transport of cotton to the shredding plant, the recycling process of cotton, and the transport of shredded cotton to the compounding plant were also considered. The assessment of composites containing rice husks included the impacts of husk milling and the transport of husks to the compounding plant. Additionally, the impact of rice cultivation was studied and allocated to rice husks on the basis of their economic value in relation to rice. For the assessment of virgin plastics, the most recent data on the production of HDPE and PP published by PlasticsEurope for SimaPro version 7.0 software (Pre 2006) were used.

The following environmental impacts lie beyond the scope of our study:

- The environmental impact of compounding additives, since their environmental burdens may be considered negligible.
- The impacts of cotton cultivation. Cotton entering the system is recovered from fabric waste.
- The impacts of further processes that may be applied to the composite materials to obtain finished products. These impacts are considered equivalent for composites and virgin plastics, and as such, they do not serve for comparative purposes.

The use of unreliable data sources was carefully avoided. In the case of materials forming the composites, the majority of data consisted of mean annual values provided by material recycling/processing firms, complemented with rigorously selected bibliographical information. In the case of plastics derived from petroleum, the quality of the data obtained from PlasticsEurope is considered to be very good, in spite of the problems derived from the cumulative nature of data pointed out by Hischier et al. (2005).

2.2 Life cycle inventory

An LCA was carried out for each new material using SimaPro version 7.0 software (Pre 2006). The input materials of these compounds—whereof the proportions are described in Table 1—are: recycled polyolefins (HDPE, PP), rice husks, and cotton fabric waste.

The data required for constructing the inventory were retrieved from various supporting databases, and several considerations were made as explained below.

2.2.1 Rice husks

The main sources for data on rice production and processing were the inventory performed by Müller (2000) within an LCA of a farmland with a socioeconomic environment and other characteristics akin to those found in Spain and the sustainability reports by Grupo SOS (2003, 2004) of Spain, which comprise an environmental assessment of its rice-processing factories in Algemesí (Spain) and Oliveira (Portugal) where paddy rice (with husk) can be milled to obtain white rice or steamed to produce parboiled rice. Energy consumptions associated with rice cultivation were extracted from Müller (2000) with the addition of data from Llanes (2003) to incorporate the energy consumption associated with the combustion of oils and greases used by agricultural machinery. Table 2 presents the data selected for the inventory of rice processing. These data were combined to produce the life cycle inventory comprising the stages of earth preparation, seed production, sowing, irrigation, fertilization, pesticide application, rice harvesting, transport, drying, milling, and sorting.

Additionally, the following assumptions were made:

- Annual rice yields in Spain vary considerably (0.5–1 kg/m^2) with yearly weather conditions. For the purposes of this study, rice yield was estimated at 0.65 kg/m^2.
- The use of fertilizers was estimated at 155 kg/ha of N, 34 kg/ha of P_2O_5, and 53 kg/ha of K_2O (Müller 2000). The application of 2 kg/ha of copper (as $CuCO_3$) for pest control was also considered.
- The anaerobic decomposition of organic matter in flooded rice fields produces methane, which escapes to the atmosphere primarily by transport through the rice plants. The annual amount of methane emitted by rice fields depends on the number of harvests, water regimes before and during cultivation period, and organic and inorganic soil amendments. Soil type, temperature, and rice cultivar also affect methane

Table 1 Composition of new developed composites

Composite (%)	HDPE+cotton	PP+cotton	PP+husks
Recycled HDPE	72	–	–
Recycled PP	–	73.2	50
Recycled cotton	20	20	–
Rice husks	–	–	45
Additives	8	6.8	5

Table 2 Inventory data per kilogram of rice husks (Llanes 2003; IPCC 2006)

Inventory data—rice husks	
Energy consumption (kWh)	
Electricity	0.237
Natural gas	0.069
Gas–oil	0.012
Inputs (kg)	
Water	0.688
Outputs (kg)	
Final waste (nonhazardous)	6.86E−03
CO_2 emissions	1.10E−02
NO_x emissions	5.50E−02

emissions (Intergovernmental Panel on Climate Change [IPCC] 2006). Estimates of methane emissions from US rice fields ranging from 220 to 1,490 kg/ha can be found in the literature. Müller (2000) estimates these emissions at 290 kg/ha. The figure used for rice fields in Spain (120 kg/ha) is an estimate provided by the Ministry of the Environment of Spain (MMA 2007).

- Rice plant growth leads to the fixation of significant amounts of CO_2. This would yield a negative output of 1.35 kg of CO_2 per kilogram of rice husks after allocation. However, Smith et al. (2001) noted that carbon found in the biodegradable fraction of composites will have been absorbed from the atmosphere relatively recently by photosynthesis during plant growth. Therefore, when this carbon is released again as CO_2 during incineration, it will reenter the natural carbon cycle. This "short-term" carbon cycle has no net impact on global warming—as the emissions offset the recent uptake of an equivalent amount of carbon dioxide—and no global warming potential (GWP) is associated with the emission of such CO_2, since the atmospheric concentration of short-cycle carbon dioxide stays relatively constant from year to year. These emissions are reported as "short-cycle" CO_2 and a GWP of zero is assigned to them.

2.2.2 Cotton linter

During compilation of inventory data on cotton recycling, the whole industrial process was considered, including cutting, milling, shredding, and washing of cotton fibers and remnants from textile factories. Additionally, the impacts associated with the transport of both input materials and final recycled products were taken into account. Usually, no water or additives are used in this recycling process, and they were, therefore, excluded from our inventory. Inventory data (Table 3) were provided by a cotton-recycling firm located in Alcoi (Spain).

Table 3 Inventory data per kilogram of recycled cotton, as provided by a cotton-recycling firm

Inventory data—recycled cotton	
Transport (40-t lorry) (km)	
From textile factory to shredder	0.50
From shredder to compounding facility	0.05
From compounding facility to extruder	0.03
Energy (electricity) (kWh)	
Shredder	0.41

2.2.3 Recycled thermoplastic

Actual data from a firm located in Alcoi (Spain) were used to compile the inventory on mechanical plastic recycling from industrial scrap (Table 4). A flux diagram of mechanical plastic recycling can be seen in Fig. 1. A mass and energy balance was performed for system inputs and outputs. In this case, transport of thermoplastic from plastic-processing plants to recycling plants has been taken into account as well.

2.2.4 Compounding

Compounding involves mixing recycled thermoplastics with the recycled materials that constitute the reinforcing

Table 4 Inventory data per kilogram of recycled plastic, as provided by plastic recycling firm

Plastic	HDPE	PP
Inputs (kg)		
Industrial waste	1.4285	1.3333
Fresh water for washing	0.0862	0.1980
Fresh water for extrusion	0.4218	0.3101
Recirculated purified water for washing	2.0354	1.1281
NaOH (s)	0.0042	0.0063
Anionic surface-active agents	0.0013	0.0013
Zinc stearate	3E−05	3E−05
Plastic concentrate	0.0200	0.0200
Lime ($CaCO_3$)	0.0017	0.0017
Flocculant ($AlCl_3$)	0.0016	0.0016
Metallic filters	0.0001	0.0001
Outputs (kg)		
Mud (65% humidity)	0.1351	0.3070
Recirculated purified water for washing	2.0354	1.1281
Evaporated water in extruder	0.4218	0.3101
Plastic pellets	1.0000	1.0000
Valorizable waste	0.4085	0.2552
Valorizable metallic filter waste	0.0001	0.0001
Energy consumption		
Electricity (kWh)	0.06400	0.06400
Gas–oil (kWh)	0.00312	0.00312
Transport (lorry 40 t) (km)		
Average route length	100	1,000

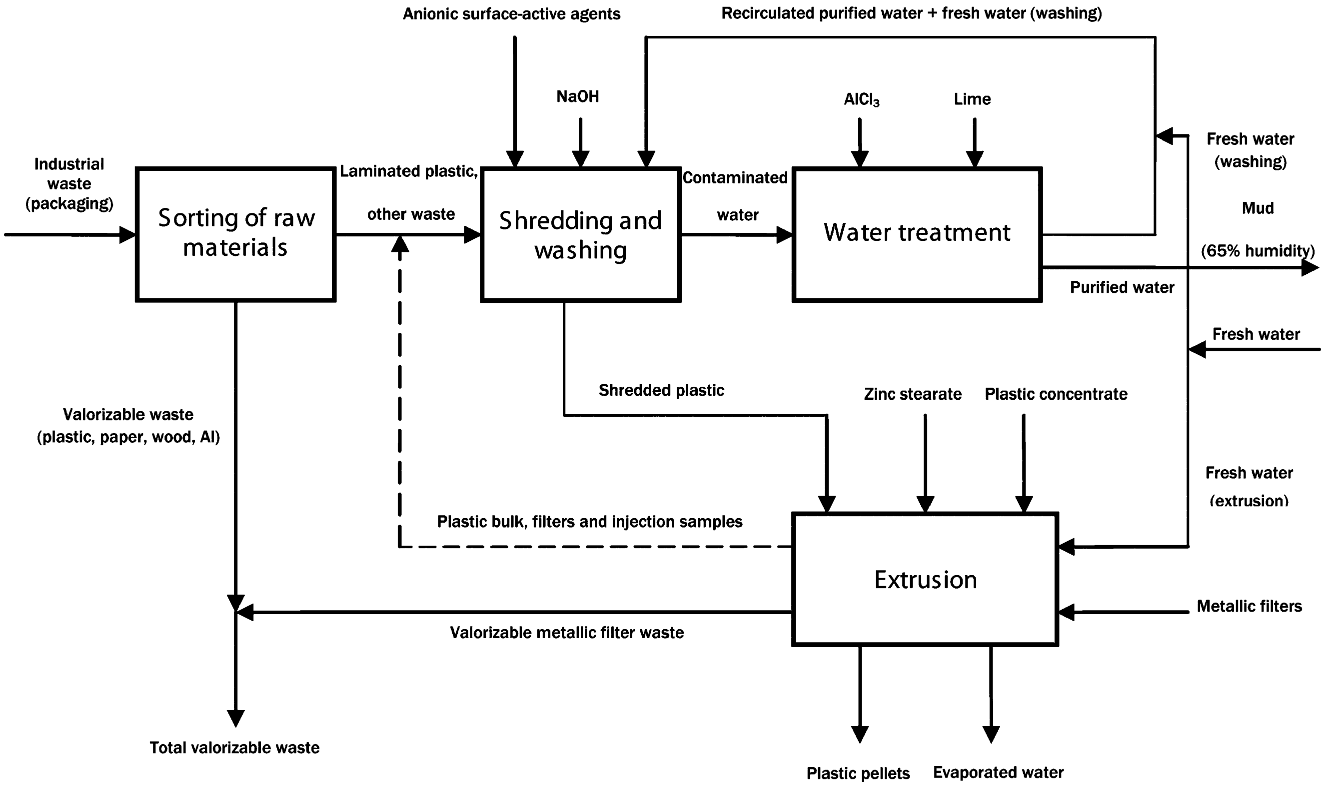

Fig. 1 Flow diagram of black HDPE recycling, adapted from Cerisuelo (2006)

filler to obtain composite materials. The inventory of this process includes electric consumption and transport of raw materials to the plant, as detailed in Table 5. Inventory data regarding electricity consumption were obtained from a compounding firm located in the UK.

2.2.5 Virgin plastic

The inventory data for the manufacturing of thermoplastics (HDPE, PP) were taken from SimaPro version 7.0 (Pre 2006), as provided by PlasticsEurope. These data are included in SimaPro and contain information from several European firms on the manufacturing of HDPE (ten firms) and PP (15 firms).

2.2.6 Allocation

In accordance with the International Organization for Standardization (ISO) 14044:2006 standard (2006), it would be advisable to avoid impact allocation. In our case study, this posed some difficulties because rice husks are a coproduct of rice with many possible applications: rice husks can be burned for energy, but they are also used to build heat insulation panelling, to provide farm animal bedding, or even act as a plant substrate. These uses can also be accomplished by many substituting products which may, in turn, be coproducts of other production systems. In order to avoid this “fuzziness” in the system’s boundaries, some allocation was performed on the basis of economic value. This

Table 5 Inventory data per kilogram of composite, as provided by compounding firm

Composite	HDPE+cotton	PP+cotton	PP+husks
Energy (kWh)			
Electricity	0.44	0.44	0.44
Transport (km)			
Recycled plastic to compounder (100 km)	0.072	0.0732	0.050
Husks/cotton to compounder (300 km)	0.060	0.0600	0.135
Additives to compounder (300 km)	0.024	0.0204	0.015

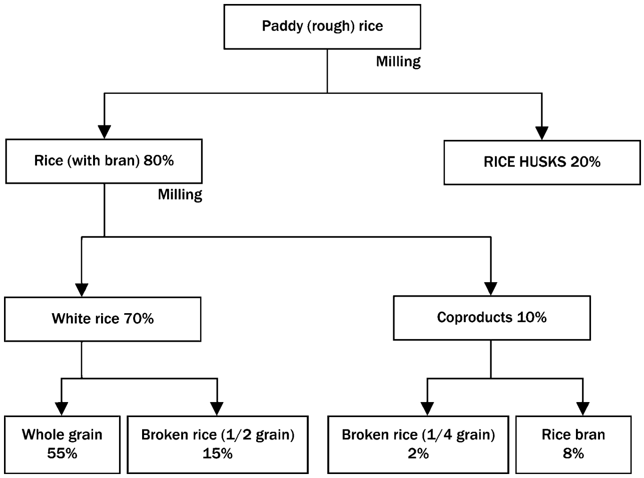

Fig. 2 Manufacturing process of rice and its coproducts from SOS (2004)

allocation process is explained next. Figure 2 shows a diagram of the manufacturing of rice, featuring the percentages of each coproduct usually obtained along the process.

In the case of Spain, there are no quoted prices for rice and its coproducts because rice is not a traded commodity—more specifically, rice husks are generally treated as waste devoid of economic value. Few countries worldwide have national rice markets, excepting those with very large productions of rice, as is the case of India, Japan, Pakistan, Indonesia, Thailand, Mexico, Brazil, Korea, or Vietnam. In the case of rice husks, only a few regional markets can be found for very specific applications, such as the production of energy from their combustion. In order to find the relationship between the values of rice—the main product—and its coproducts, data from Colombia, Argentina, the Indian state of Punjab, and the province of Jalisco in Mexico were compared. Table 6 shows the mean values of rice coproducts over recent years in the aforementioned areas.

From the previous table, we can infer a relationship between the economic value of polished (white) rice and its coproducts. Even though the nominal prices of rice coproducts vary greatly among countries, the underlying relationships among them are very similar. In spite of the sharp socioeconomic differences between the two regions, the economic value of rice husks in relation to that of white rice is practically the same—around 15%—in Punjab and Jalisco, which suggests it is reasonable to use this figure for allocation. Looking at the economic value of the rest of rice coproducts, we can obtain similar relationships between their economic value and that of white rice on the basis of the data from Colombia and Argentina. Once the relationships between white rice and all coproducts are thus estimated, these values can be averaged and converted in relation to the economic value of rice husks, so as to be applicable to the assessment of our rice husk composite. The results of this procedure are shown in Table 7.

2.3 Impact assessment

2.3.1 Selection of impact categories

The impact assessment performed in this paper comprised the classification and characterization of environmental impacts. In accordance with ISO 14044:2006 (2006), impact weighting was avoided for comparisons.

There is no scientific consensus regarding which impact categories should be considered when assessing the environmental impacts associated with biopolymers and composites. Since 2003, several LCA studies of polymers have been published. In spite of the great methodological differences found among them, greenhouse effect and nonrenewable energy depletion are unanimously selected as relevant impact categories. Two other categories—namely, eutrophication and acidification—are broadly selected. A vast majority of researchers use impact categories included in Guinée's list (2002). Hence, the four impact categories selected in this study were global warming, nonrenewable energy depletion, acidification,

Table 6 Market value of white rice and its coproducts by region/country

Country or region of study	Punjab (India)[a]	Jalisco (Mexico)[b]	Colombia[c]	Argentina[d]
Period of study	Dec. 02–Jul. 05	Jan. 05–Apr. 06	Jan. 05–Jan. 06	Jan.05–Jan.06
Product (price [$/kg])				
White rice	0.228	0.555	0.472	0.272
Broken rice (1/2 grain)	–	–	0.240	0.141
Broken rice (1/4 grain)	–	–	0.188	0.115
Rice bran	–	–	0.154	0.115
Rice husks	0.038	0.079	–	–

[a] CDM—Executive Board (2002)
[b] Sistema nacional de información e integración de mercados (2006)
[c] Federación nacional de industriales del arroz (2006)
[d] Secretaría de agricultura, ganadería, pesca y alimentos (2006)

Table 7 Mean economic values of rice and its coproducts in reference to rice husks

Product	Economic value in relation to husks (%)
White rice	649.20
Broken rice (1/2 grain)	332.99
Broken rice (1/4 grain)	266.86
Rice bran	243.79

and eutrophication. Further discussion on the selection of impact categories relevant to the assessment of biopolymers and composites can be found in Vidal et al. (2007).

2.3.2 Global warming

In order to compare the impacts of emissions of different greenhouse gases (GHG), each gas was assigned a GWP index, expressing the ratio between the increase in infrared absorption due to the instantaneous emission of 1 kg of a given substance and that due to an equal emission of CO_2, both integrated over time.

Based upon the expert judgement of scientists worldwide, the IPCC has compiled a list of provisional best estimates for GWPs with time horizons of 20, 100, and 500 years. This list of GWPs is periodically updated. The last update was published in 2007 (IPCC 2007). GWPs over a hundred years (GWP100) are generally recommended as the baseline characterization method for the global warming category.

2.3.3 Nonrenewable energy depletion

Nonrenewable energy depletion encompasses the use of both nonrenewable and renewable abiotic resources, although in this study, we limited the analysis to the depletion of nonrenewable energy sources alone. Our study uses the method proposed by Van Oers et al. (2002), including modifications related to available reserves and the addition of subcategories, one of them being fossil fuels depletion. Fossil fuels include oil, natural gas, and coal. The category indicator for nonrenewable energy depletion is measured in megajoule equivalents.

2.3.4 Acidification

Acidic gases, such as sulfur dioxide, nitrogen oxides (released during the burning of fossil fuels), and other acidic releases (such as sulfuric acid emissions from the production of fertilizers), contribute to the acidification of soil and fresh water ecosystems. The category indicator for atmospheric acidification is measured in kilograms of sulfur dioxide equivalents. In this study, the average European characterization factors of Huijbregts (1999) were used.

2.3.5 Eutrophication

Periodic releases of nitrates and phosphates to fresh water catchments and marine waters increase nutrient buildup. Excessive accumulation of nitrates and phosphates creates algal blooms and consequently depletes dissolved oxygen content. The method adopted in this study is the one described by Heijungs et al. (1992) in which all emissions of N and P to air, water, and soil and of organic matter to water are aggregated into a single measure. This allows for both terrestrial and aquatic eutrophication to be assessed. The category indicator for eutrophication is measured in PO_4^{3-} equivalents.

3 Results

3.1 Manufacturing phase

In order to assess the environmental impact of the manufacturing phase of composites, the inventory data related to the acquisition of raw materials and the compounding phase were taken into account to enable the comparison of the results with those corresponding to virgin plastics.

The composites subject to analysis exhibited a significantly reduced environmental impact during the materials acquisition and processing phases compared to conventional virgin thermoplastics in all of the impact categories considered. The use of fertilizers for rice cultivation, however, impaired the results of the rice husk composite in the eutrophication category where it nevertheless outperformed its conventional counterparts (Table 8).

Table 8 Environmental impact of 1 kg of composites and conventional plastics

Impact category	Unit	HDPE+cotton	PP+cotton	PP+husks	Virgin HDPE	Virgin PP
Global warming	kg CO_2 eq	0.61	0.70	0.71	1.88	1.99
Nonrenewable energy depletion	MJ eq	10.77	12.02	8.63	75.98	75.46
Acidification	kg SO_2 eq	4.03E−03	4.25E−03	4.87E−03	2.14E−02	2.03E−02
Eutrophication	kg PO_4^{3-} eq	2.67E−04	3.63E−04	9.34E−04	1.30E−03	1.26E−03

Table 9 GHG fluxes associated with the disposal of 1 kg of composites and conventional plastics by composting scenario

Emissions (kg CO_2 eq)	Incineration			Landfilling		
	Virgin plastic	HDPE/PP+cotton	PP+husks	Virgin plastic	HDPE/PP+cotton	PP+husks
Percent C	85.70	76.90	61.31	–	–	–
Percent biodegradable material	–	–	–	0	8.42	16.56
Short-cycle CO_2 (GWP=0)	0	0.3087	0.6072	–	–	–
Fossil CO_2 (GWP=1)	3.1423	2.4353	1.6026	–	–	–
N_2O (GWP=296)	5E−05	5E−05	5E−05	–	–	–
Sequestered CO_2 (GWP=−1)	–	–	–	0	0.3087	0.6072
Fossil CO_2 (energy and transport) (GWP=1)	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080
Total GHG	3.1651	2.4581	1.6254	0.0080	−0.3007	−0.5992

3.2 Disposal phase

The environmental impact of disposing of composites and virgin thermoplastics waste was focused on the global warming impact category because CO_2 emissions (and, to a lower extent, CH_4 emissions) are the most significant in this case. The methodology developed by Smith et al. (2001)—updated with the characterization factors of IPCC (2007)—was applied to two scenarios: incineration without energy recovery and landfilling without gas control.

The key to determining CO_2 emissions is the proper calculation of C concentrations and the proportions of fossil and "short-cycle" carbon present in the waste. Carbon concentrations for PP and HDPE (85.7%) were calculated considering the chemical formulations of the polymers and assuming that the material (1 kg) is dry in both cases. In the case of rice husks (36.8%) and cotton linters (42.1%), data were extracted from Bhattacharya et al. (2000) and Haykiri-Acma and Yaman (2007), respectively.

The main noncarbon GHG of interest to waste management is N_2O. Nitrous oxide is formed in trace amounts from nitrogen gas present in the air and from compounds of the element found in waste during combustion in incinerators, landfill gas flares, and combustion engines (Smith et al. 2001).

3.2.1 Incineration

The incineration of conventional plastics makes a net positive contribution to global warming, whereas the incineration of the organic fraction of bio-based materials as "short-cycle" carbon compounds is neutral in global warming terms.

According to Smith et al. (2001), "short-cycle" CO_2 has a GWP of zero. Fossil fuel reserves constitute an almost-permanent sink for carbon, but their combustion releases the stored carbon into the atmosphere as fossil-derived CO_2. These emissions are reported as "fossil CO_2" and have the usual GWP of one. Emissions of N_2O from incinerators and of CO_2 from energy consumption and transport of materials were estimated at 0.05 and 8 kg/t, respectively (Smith et al. 2001).

The incineration of 1 kg of virgin thermoplastic (PP or HDPE) causes the emission of 3.1651 kg of CO_2 eq. Incorporating biodegradable waste into the material can reduce these emissions by up to 49% (Table 9).

3.2.2 Landfilling

Conventional plastics are not degraded in landfills. The newly developed composites are expected to behave similarly because their organic fraction is encapsulated by the thermoplastic, hence preventing contact with air, water, or microorganisms that would cause their degradation and the subsequent release of GHGs. Thus, methane emissions from the degradation of composite materials are not accounted for. CO_2 emissions sequestered in this fashion were calculated from the proportion of C found in cotton and rice husks, and they were assigned a GWP of −1.

Small amounts of N_2O may be released from landfill gas flares, but these were deemed too small to make a significant contribution and were, therefore, omitted (Smith et al. 2001). Emissions of CO_2 from energy consumption and transport of materials were estimated at 8 kg/t (Smith et al. 2001). The disposal of composites to landfill showed clear environmental benefits, especially in the case of rice husk composites due to their higher carbon content (see Table 9).

3.2.3 GHG savings

Whether composites are incinerated or taken to landfill, GHG savings are achieved in comparison with their conventional

Table 10 GHG savings of composites in relation to their conventional counterparts

kg CO_2 eq/kg virgin plastic	Incineration	Landfilling
HDPE+cotton	1.977	1.579
PP+cotton	1.995	1.597
PP+husks	2.824	1.892

counterparts. Overall, GHG emissions associated with 1 kg of HDPE—considering manufacturing processes and incineration—are estimated at 5.054 kg of CO_2 eq (see Tables 8 and 9), while obtaining 1 kg of composite HDPE+cotton linters leads to the emission of 3.068 kg of CO_2 eq—roughly a 40% improvement. GHG savings were calculated similarly in the other cases (Table 10).

4 Discussion

In spite of the results obtained in our case study, a general conclusion about the environmental efficiency of composites compared to conventional products cannot be drawn unless individual assessments are performed. Some authors (Braschkat et al. 2004; Gärtner and Reinhardt 2004; Patel et al. 2003; Scott 2000) have pointed out that biodegradable plastics, biocomposites, or composites may, in some cases, be less "ecological" than conventional plastics. This paradoxical situation can be attributed, among other reasons, to the high degree of optimization attained by conventional plastic industries. In contrast, composite processing techniques often lack optimization, as they are still in an incipient state of development. In the future, as mass production of these plastics becomes more widespread, their environmental impact can be expected to reach lower levels than those reflected in our study. Therefore, further research on the optimization of their processing toward their environmental improvement should be conducted (Känzig et al. 2003).

The incorporation of biodegradable waste into composite materials prevents the consumption of natural resources and the disposal of waste. Additionally, the composites studied may—akin to conventional thermoplastics—be incinerated with energy recovery. However, they cannot be easily recycled, albeit the use of a biodegradable matrix would allow for the valorization of composite waste as compost.

Differences between the densities of composites and conventional thermoplastics cannot be overlooked for those products whose functional unit is given in terms of volume. In those cases, the environmental benefits would be reduced by 8% in the case of HDPE+cotton linter over virgin HDPE and 20% in the case of PP+rice husks over virgin PP.

5 Conclusions

Composites subject to analysis exhibited a significantly reduced environmental impact compared to conventional virgin thermoplastics using 1 kg of material as a functional unit.

Waste disposal should not be neglected in the environmental assessment of composites, as results in global warming terms may vary dramatically depending on the disposal method employed.

6 Recommendations and perspectives

In accordance with the ISO 14044:2006 standard (2006), it would be advisable to avoid impact allocation. This posed some difficulties, since rice husks are a coproduct of rice. Thus, some allocation was done in our study on the basis of economic value.

Given the relation between crops and composites, it would also be advisable to take the land use impact category into consideration when performing comparative studies between composites and conventional plastics to account for the land used to obtain the organic fraction of biomaterials, the land use associated with the disposal of composites to landfill, or even the esthetic impact thereof. However, as stated in Milà i Canals et al. (2006), the definition of this category is currently the subject of scientific debate. No reliable methodologies have yet been developed for the assessment of the land use impact category, in spite of its crucial long-term implications on soil quality. A discussion on land use in LCA can be found in Garraín et al. (2007a, b).

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